A Comparative Study of Modal Properties of Surface-Emitting Circular Bragg Micro-Lasers

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Abstract: Modal properties of two types of surface-emitting circular Bragg micro-lasers (CBMLs) are compared. Disk CBMLs are suitable for low-threshold, high-efficiency, ultracompact laser design, while ring CBMLs are an excellent candiadate for high-efficiency, large-area, high-power applications.

Keywords: Surface-emitting lasers; Semiconductor lasers; Bragg lasers; Modal property; Integrated optoelectronics

1. Introduction

Surface-emitting lasers with a circular emission aperture are particularly useful in optical communications because they can produce circularly-symmetric, narrow-divergence laser beams [1-3]. With optical gain, circular Bragg micro-resonators can be engineered for such applications – the radial Bragg reflector not only provides feedback for the in-plane fields but also couples the laser radiation out of the plane vertically. The lasers based on such circular Bragg resonance are referred to as circular Bragg micro-lasers (CBMLs).

Similar to the circular resonators, the CBMLs can be classified into two configurations: disk- and ring- CBMLs. As shown in Fig. 1, disk CBML has a center disk surrounded by a radial Bragg grating extending from x_0 to x_b. Ring CBML has an annular defect surrounded by inner and outer gratings which extends, respectively, from the center to x_L and from x_R to x_b. In this paper we compare their modal properties such as modal field pattern, threshold gain, detuning factor, and far-filed pattern. In order to demonstrate their advantages as surface-emitting lasers, circular DFB laser will be introduced as a reference in comparing the quality factor, emission efficiency, and modal area.

2. Comparison of Modal Properties of Surface-Emitting CBMLs

The characteristic equations which govern the laser modes were derived in [4] by resonance condition theory:

$$\frac{e^{2(g_A-i\delta)x_0}\nu\sinh[S(x_b-x_0)]}{(u-i\delta)\sinh[S(x_b-x_0)]-S\cosh[S(x_b-x_0)]}=1 \quad \text{for disk CBML,}$$

and

$$\frac{e^{2(g_A-i\delta)(x_R-x_L)}\nu\sinh[S(x_b-x_R)]}{(u-i\delta)\sinh[S(x_b-x_R)]-S\cosh[S(x_b-x_R)]}\times\frac{(u-\nu-i\delta)\sinh[Sx_L]+S\cosh[Sx_L]}{-(u-\nu-i\delta)\sinh[Sx_L]+S\cosh[Sx_L]}=1 \quad \text{for ring CBML.}$$

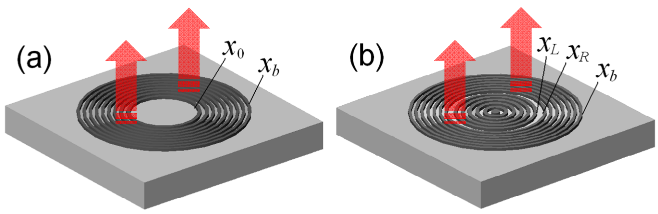
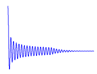
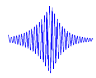
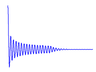
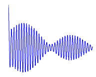
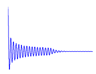
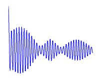
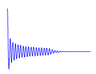
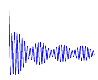
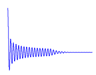
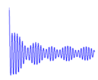


Fig. 1. Illustrations of surface-emitting CBMLs: (a) Disk CBML and (b) Ring CBML. Laser radiation is coupled out of the plane in vertical direction by the first-order scattering.

TABLE I
MODAL FIELD PATTERNS, THRESHOLD GAINS (g_A, IN UNIT OF 10^{-3}), AND FREQUENCY DETUNING FACTORS (δ, IN UNIT OF 10^{-3}) OF THE DISK CBML AND RING CBML WITH EXTERIOR BOUNDARY RADIUS $x_b = 200$

Laser type	Disk CBML			Ring CBML		
	Modal field	g_A	δ	Modal field	g_A	δ
Mode 1		0.127	49.8		0.457	55.9
Mode 2		0.288	21.2		1.06	66.9
Mode 3		0.454	−8.09		1.92	71.0
Mode 4		0.690	−37.4		3.14	84.4
Mode 5		1.21	−66.5		4.09	91.6

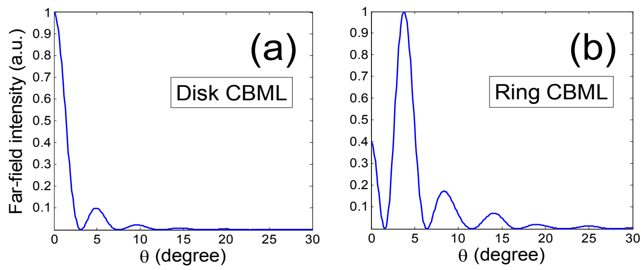


Fig. 2. Far-field intensity patterns of the fundamental modes of disk CBML and ring CBML (both with $x_b = 200$).

In the left equations, g_A is the gain coefficient. $\delta = (\beta_{\text{design}}-\beta)/\beta$ is the frequency detuning factor, where β is the in-plane propagation constant. u and ν are defined as $u = g_A - h_1$, $\nu = h_1$

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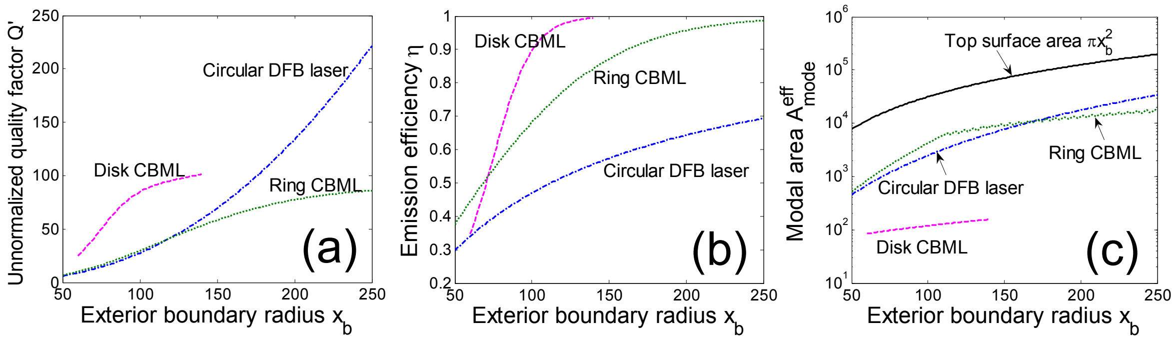

Fig. 3. (a) Unnormalized quality factors, (b) emission efficiencies, and (c) modal areas of the fundamental modes of disk CBMLs (dashed), ring CBMLs (dotted), and circular DFB lasers (dash-dot).

$+ ih_2$, where h_1 and h_2 are the radiation- and feedback-coupling coefficients which can be precalculated. S is defined as $S = [(u - i\delta)^2 - v^2]^{1/2}$. It should be noted that these characteristic equations implicitly includes the effect of vertical radiation for nonzero h_1.

Modal field patterns, threshold gains g_A, and frequency detuning factors δ of the disk- and ring- CBMLs are listed in Table I for devices with $x_b = 200$. For disk CBML, the inner disk radius $x_0 = x_b/2$. For ring CBML, the annular defect is assumed to be located at $x_b/2$ with its width being a wavelength such that $x_L + x_R = x_b$ and $x_R - x_L = 2\pi$. As shown in Table I, all the displayed modes of disk CBML are confined to the center disk with negligible peripheral power leakage and thus possess very low thresholds and very small modal areas. For ring CBML, each mode needs a higher threshold gain than that of the disk CBML, but they also possess large modal areas which is advantageous for large-aperture, high-power surface emission.

Far-field intensities are calculated based on Fourier transform of the radiation fields at the emission aperture. Shown in Fig. 2, the disk CBML has most of the energy concentrated in the zeroth-order Fourier component thus its peak is located at the center, while the ring CBML has the first-order lobe dominating thus features a donut shape.

In what follows we also include circular DFB laser as a reference to show the advantages of CBMLs as surface-emitting lasers. To compare quality factor, an unnormalized

$$Q' = \frac{\int_0^D Z^2(z)dz \cdot \int_0^{x_b} |E(x)|^2 \, xdx}{\int_{\text{grating}} |\Delta E(x, z=0)|^2 \, xdx + \int_0^D Z^2(z)dz \cdot |E(x=x_b)|^2 \, \beta x_b}$$

is used whose nominator represents the store energy and the denominator the total power loss. D is the resonator thickness and Z is the vertical modal profile. $E(x)$ denotes the in-plane modal field and $\Delta E(x,z)$ the radiation field where the emission aperture is located at $z = 0$. Fig. 3(a) shows increases in the device size (x_b) result in enhanced Q' values. Additionally, the disk CBML exhibits a much higher Q' than the other two laser structures of identical dimensions, which is consistent with the threshold behaviors shown in Table I.

The emission efficiency η is naturally defined as the fraction of the total power loss which is represented by the useful vertical radiation. Fig. 3(b) demonstrates a larger η for devices with a larger size (x_b). As seen from comparison, only the disk- and ring- CBMLs achieve high emission efficiencies. This is because their fundamental modes are bandgap modes while that of the circular DFB laser is an in-band mode.

The effective modal area in a 2-D case is defined as

$$A_{\text{mode}}^{\text{eff}} = \left[\iint |\mathbf{E}|^2 \, xdxd\varphi \right] \Big/ \max\{|\mathbf{E}|^2\},$$

where x and φ are radial and angular coordinates, respectively. It is a measure of how the modal field is distributed in the laser. Plotted in Fig. 3(c), the modal area of the disk CBML was found to be the smallest. This is not surprising and can be inferred from their unique modal profiles listed in Table I. Actually our prior experimental work has demonstrated single-mode lasing with ultrasmall modal volume in a nano-sized disk CBML fabricated in InGaAsP [3]. Clearly, a disk configuration is preferable in ultracompact laser design. Alternatively, ring CBMLs have a large modal area with high emission efficiency, rendering them suitable for high-efficiency, high-power, large-area laser applications.

3. Conclusions

By comparing the modal properties of disk- and ring-CBMLs, we demonstrated their advantages as surface-emitting lasers and concluded that disk CBMLs are most useful in low-threshold, high-efficiency, ultracompact laser design, while ring CBMLs are excellent candidates for high-efficiency, high-power, large-area lasers.

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